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NAVIGATION IN THE AGE OF NETWORK CENTRIC WARFARE

by

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A paper submitted to the Faculty of the Naval War College in partial satisfaction of the requirements of the Department of Joint Military Operations.

The contents of this paper reflect the opinions of the author and are not necessarily endorsed By the Naval War College or Department of the Navy.

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With the coming of Network-Centric Warfare (NCW) and the information superiority it will provide, the Joint Commander must be able to control, exploit and disseminate navigation information just like any other battlespace-critical factor. By incorporating geospatial information as a subset of overall battlespace awareness, we can ensure the robust and reliable navigation information flow that will allow the Joint Commander to dominate the battlespace of the future.

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Abstract of

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In today's military, navigation of platforms, personnel and weapons centers around the use of the Global Positioning System (GPS). Whole weapons programs rely on GPS for their precision strike capability. While offering a level of accuracy unheard of a couple of decades ago, GPS is vulnerable to asymmetrical attack in the form of jamming and spoofing. Because of the platform-centric nature of our current navigation architecture, the Joint Commander has virtually no ability to control weapons in the event of a GPS failure. Additionally, he has no ability to provide networked navigation information or provide error control of navigation information to his forces.

With the coming of Network-Centric Warfare (NCW) and the information superiority it will provide, the Joint Commander must be able to control, exploit and disseminate navigation information just like any other battlespace-critical factor. By incorporating geospatial information as a subset of overall battlespace awareness, we can ensure the robust and reliable navigation information flow that will allow the Joint Commander to dominate the battlespace of the future.

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INTRODUCTION

Electronic navigation has radically improved every aspect of military operations over the last decade. Whether in the area of precision guided munitions (PGMs), nap-of-the-earth flying or cross-country movement of troops, electronic navigation has given geo-location unprecedented accuracy and availability. Once measured in hundreds of meters, the Global Positioning System (GPS) has improved navigational accuracy to a few meters or better over long distances. Across the spectrum of warfare, the implications of precision positioning are impressive. Munitions can be placed accurately enough that individual vehicles, buildings or other objects can be targeted with minimal probability of collateral damage. Ground troops and Special Warfare personnel can navigate over many miles of foreign terrain with pinpoint accuracy. Aircraft and ships can employ standoff weapons that incorporate smaller warheads and achieve surgical precision. Perhaps most importantly, precise geo-location of friend and foe allows commanders to view an accurate three-dimensional picture of the battlespace. The real essence of Network-Centric Warfare (NCW) has begun to emerge[1].

GPS, a key enabler of this revolution, will continue to be of tremendous utility to our military and civilian users, but there are in total reliance on GPS and other radio-navigation techniques. The impact information technology will have on command and control should not depend on one system. Even so, we have begun building weapons systems based heavily on GPS for precision guidance. The Joint Direct Attack Munition (JDAM), Extended Range Guided Munition (ERGM), Tactical Tomahawk (TACTOM) and the Joint Standoff Weapon (JSOW) are, to be sure, terrific force multipliers and allow unprecedented strike accuracy[2]. Is it prudent, however, to place the burden of precision navigation on any external reference system that is vulnerable? We have the technology to build a robust and precise navigation

architecture that takes full advantage of all of our navigation systems and our Geospatial Information Systems (GIS) infrastructure. There are alternatives that can provide all of the benefits of GPS, fit well into the NCW framework, and virtually eliminate the possibility of outside interference. Utilizing complete, multi-spectral navigation systems, the joint commander can control all assets at his disposal in the synergistic way that NCW promises without fear of asymmetric threats to his navigation capability[3].

NAVIGATION NOW AND IN THE FUTURE

GPS can provide extraordinary precision with excellent availability. Military-grade receivers can be made in shirt-pocket size and can be used anywhere there is a clear path to the sky. Since the receivers do not transmit, they offer no cueing to potential adversaries. Each satellite, part of a constellation that orbits the Earth 11,000 miles out, transmits a weak signal to Earth. Our adversaries know the GPS frequencies and can easily build jammers capable of wiping out the system over an area of a few hundred kilometers. Russia markets such a man-portable jammer for a few thousand dollars with a claimed jamming area 200 kilometers in diameter. Even if replacement satellites with considerably greater power and anti-jam technology are procured, the system will continue to be susceptible to jamming[4].

GPS coverage during Desert Storm nearly suffered a major setback when a recently launched satellite was improperly positioned. Improvisation and luck managed to give coalition commander and his forces adequate coverage, but the implication of failed artificial satellites was a concern for the Combined Task Force Commander.

Spoofing, or tricking, of GPS is possible. Inadvertent spoofing occurs with regularity in some parts of the world as a result of many phenomena[5]. Signals bouncing off of cars, buildings and natural objects produce errors in position. Physical features such as mountains

can block signals or introduce additional errors[6]. GPS is a valuable asset, but is not infallible. Perhaps the best illustration of excessive reliance on GPS is a plausible scenario:

Scenario 1: in the near future

The time: 0100 in the year 2008

Location: 30 miles off the coast of a hostile country

A U.S. embassy has been besieged and the nearby Amphibious Ready Group (ARG) led by *USS Essex* (LHD-2), with the Joint Task Force Commander embarked, is to make an opposed landing. Ships in company include the *USS Carney* (DDG-64). The beachhead is defended by a few surface to surface missile emplacements, several surface to air (SAM) sites and a small number of light infantry.

Supporting the operation are squadrons of F15 Strike Eagles and F16 Suppression of Enemy Air Defense aircraft from an in-theater airbase. The operation will involve the closely timed destruction of the SAM installations followed by destruction of the surface to surface missile sites. Afterwards, Naval Surface Fire Support (NSFS) from *Carney*, using Extended Range Guided Munitions (ERGMs) and Tactical Tomahawk (TACTOM) missiles, will suppress enemy troop action along the first dune line on the beach[7].

In close proximity to the defensive emplacements are several homes and businesses of the surrounding city. The embassy is just inland and the number of American citizens to be rescued requires use of new high-speed amphibious assault craft, air cushion landing craft, helicopters and vertical takeoff and landing aircraft. Timing is critical since heavily armed reinforcements are on their way.

One hour after launching of the aircraft sorties, GPS is jammed from several ground and airborne locations wiping out GPS for a radius of 200 miles. The first landing wave has

just begun heading to the beach. Confusion takes hold as several unexpected events occur. On board *Essex*, the linked, computer-based system used to provide command and control over the amphibious craft loses its GPS navigation input. There are no ground transmission sites to allow further updates, so the craft proceed using inertial and magnetic systems. However, due to lack of training in the older systems, confusion ratchets up to the next level. The long distance run to the beach and the perplexed operators increase the likelihood of large errors in landing location. Time lost due to navigation errors and resultant disarray of the landing forces may result in the inability to carry out the evacuation. Marines on board the landing craft have just lost the use of 2 dozen hand-held GPS units and must now rely on a few compasses, poor maps and flashlights to navigate once ashore. They are lost.

Carney maintains radar contacts on our inbound aircraft but 45 minutes later the tactical data link picture on board *Carney*, *Essex* and other vessels in company diverges. The situation becomes even more confusing to the Commander. With no GPS updates, the shipboard inertial navigation systems provide steadily degrading navigation inputs to the tactical picture. The picture on the joint command information network becomes cluttered and uncertain since it is now being updated from alternate navigation sources and not in real time[8]. Two differing pictures emerge on each vessel and add to the confusion. The on scene track coordinator must now decide which of the inputs for the tracks, held by all ships, is the most accurate. With *many* possible combinations, the task is formidable. The Joint Task Force Commander now has no battlespace picture with which to evaluate and manage the operation. The Fog of War has become very dense.

"A hussar or scout leading a patrol must find his way easily among the roads and tracks. All he needs are a few landmarks and some modest powers of observation and imagination. A commander-in-chief, on the other hand, must aim at acquiring an overall knowledge of the configuration of the province, of an entire country. His mind must hold a vivid picture of the road-network, the river-lines and the mountain ranges, without ever losing sense of his immediate surroundings."

Carl Von Clausewitz[9]

Pilots flying the F16s are able to use anti-radar missiles to take out the active SAM sites, but the F15s and their weapons, now using only inertial navigation, cannot ensure accurate strikes against the surface to surface sites and must return to base. Despite the command and control network at the Commander's disposal, he cannot provide the airborne forces with linked navigation data and loses the aircraft as an asset. *Carney*, losing GPS input to the ERGMs and TACTOMs, suspends fire support for fear of friendly fire casualties and excessive collateral damage. With loss of all supporting fires, the landing craft and support aircraft are forced to return to their ships until the situation can be re-evaluated. The Joint Task Force Commander has lost control of the situation due to navigation failures and our embassy falls.

Failure of this operation did not result from the failure of GPS, but a failure in the way the navigation information was collected and distributed. Traditional weapons and the way they were employed did not require precision navigation. As a result, there was no "network" of shared navigation data or redundancy at the level required for precision weapons. We always assumed that as long as we could get to point B from point A, we could carry out our mission. Joint Commanders of today must not only be able to get to the area of operation, but must be able to constantly measure, define and influence the area of operation. Command and control in the NCW age implies command and control of people, platforms *and weapons* from point of maneuver to point of attack.

Despite its vulnerability, the services appear to be relying on GPS more and more. Evolving Navy and Marine Corps doctrine calls for a switch from near-shore amphibious operations to distant or even over-the-horizon operations. Operational Maneuver from the Sea (OMFTS) involves the use of long-range amphibious craft, helicopters and vertical takeoff and landing aircraft. All of these platforms rely on GPS for their primary navigation input. Amphibious command and control systems in development now will use GPS as the primary source for navigation, location and timing functions[10]. In an amphibious assault from 1500 yards off the beach this is certainly not an issue, but the new doctrine calls for landings from *many miles* out at sea with no visual references. These new command and control systems are an example of a fledgling use of NCW technology. A three-dimensional picture is provided to the Joint Commander aboard ship. From the command and control spaces he can not only see all the forces at his disposal, he can control each unit independently since each unit is located individually within a common geospatial reference system. The next step in this revolution will be his ability to bring the most efficient weapons to bear based upon distributed information about foes within the same reference system. Shooters may target different objectives at different places at the same time. Operational commanders will have unprecedented control and knowledge of the battlespace from 50 miles out at sea to well inland. New amphibious ships, of which the LPD-17 class is the first example, will employ NCW concepts based heavily upon GPS as the navigation method. Every new weapons platform is similarly dependent[11].

Scenario 2: same situation, further in the future.

The time: 0100 in the year 2015

Location: 30 miles off the coast of a hostile country

Advances in NCW technology have resulted in major changes to the command and control system in use. Navigation has been integrated into all of the supporting data networks and is part of a multi-sensor system.

A new class of amphibious assault ship has been placed into service and the *USS Grenada* (LPD-21) is the Amphibious Ready Group flag ship. The Joint Task Force Commander has the *USS Trent Lott* (DDG-28), a Land Attack Destroyer, available for surface fire support. The rescue will once again be accomplished using organic amphibious craft and aircraft. Air Force assets available are F-22 Advanced Tactical Fighters carrying both enemy air defense suppression weapons and standoff surface to ground missiles.

Within an hour of receiving the tasking, the command and control systems aboard the ships at sea, aircraft aloft and all supporting craft receive their platform-tailored, mission-specific geospatial database. Bathymetry, gravity, high-resolution topography of the inland areas, weather, imagery and a variety of other overlays can all be linked to all of the various platforms.

As soon as the first assault wave heads for the beach, powerful GPS jamming begins from many locations. The Commander orders alternate navigation data to be linked as the primary source to all units. Utilizing the integrated gravity, inertial and bathymetry-matching backup systems aboard *Grenada*, precise positioning of all units is maintained by tracking them with radar systems and directional positioning beacons. Aircraft on their way to their targets use both the navigation data link from the ships and their on-board inertial and

terrain-matching backups to continue their mission. Error correction for their systems is provided from the master navigation plot aboard *Grenada*.

Minutes prior to the first F-22 strike, the Commander receives new intelligence that one surface-to-surface missile site has been surrounded with human shields from the local population. He decides to avoid this target and directs that it be removed from the programmed strike list. At the moment of the order, however, the first F-22 has just released ordnance selected for that target. Data linked to the command and control system from the *Lott's* Aegis radar shows the missile in flight. The Commander's programmed secondary target is selected and navigation inputs are made from *Grenada*. The missile changes its course and hits the secondary target.

All craft in the first assault wave lose GPS as well and automatically pick up navigation input from the assault direction system aboard *Grenada*, correcting any errors in their inertial systems. Positions of all craft monitors, as well as speed of advance and environmental conditions that might affect their progress, are displayed on the Commander's battlespace. Situations that require the Commander to modify the original course, speed of advance or landing site can be relayed instantaneously to all of the craft along with navigational data required.

Surface fire support from *Lott* proceeds using linked navigation updates to the GPS-guided ERGMs and TACTOMs. Imagery data from the overhead unmanned aerial vehicles, linked in real time to the Commander's staff, indicates troops are further inland than expected. The Commander orders adjustments to the fire support and several rounds already in the air are redirected further inland and find their mark.

Once Marines are on the ground they discover that navigation within the city is difficult without GPS. An encrypted beacon signal is relayed to overhead, unmanned aerial vehicles that triangulate the Marines' position. This data is relayed to *Grenada* and, using her navigation master plot, is able to provide position information to the Marine commander on the ground. The Joint Commander is able to monitor the progress of the ground forces continuously by this method.

New overhead imagery shows that two of the surface to surface missile sites have been moved a few hundred feet. Utilizing the navigation database, the staff is able to update target position lists over the command and control net and the Commander orders the aircraft systems to be updated via the tactical data links. All targets, with the exception of the human-shielded surface to air site, are destroyed and landing forces are able to carry out their mission. Our aircraft can now fly with impunity over the area. Despite a total loss of GPS in the area, our forces continue with their mission and successfully rescue all personnel at the embassy.

NAVIGATION IN THE NETWORK CENTRIC ENVIRONMENT: A DIFFERENT APPROACH

During the 1940s this scenario would have involved the use of iron dumb bombs, unguided projectiles from huge battleship guns, and large numbers of troops storming a beach under fire. Joint Commanders of the day didn't need *control* over the flow of geospatial information. We assembled our forces, pointed them in the right direction and let them go about their tasks. Political climate of today and the imperative to limit collateral damage and civilian loss of life have required development of precision weapons and smaller, more capable forces. Less is better seems to be the trend for many reasons. As a

result, Joint Commanders must be able to exert control over many more factors in the battlespace than in the past. This evolving command responsibility will be further accelerated by the introduction of new NCW technology and will likely push the limits of our commanders.

To ensure his command over the battlespace, even faced with rapidly changing conditions and the effect of friction, the commander needs the ability to control lethal fire during any phase of an operation. At the heart of making rapid adjustments lies the ability to know the location and disposition of his forces, and that of the enemy. NWC command and control revolves around precise, continuously updated geospatial relationships of our forces, the enemy and geophysical features. The "where am I" question is only the instantaneous component of navigation. Position, terrain, gravity, magnetic field and environmental conditions are subsets of the complete navigation picture. Using each to provide continuous, precise navigation information to the joint commander is the challenge. Fusion of these elements facilitates the creation of navigation "infostructure", a subset of the larger battlespace infostructure[12]. NCW battlespace awareness theory offers a solution that is viable now and in the future[13]. Using the battlespace model, navigation data is provided to both individual units and the C2 architecture. Reference platforms, such as large ships or fixed locations, will provide reliable, unbroken navigation data to all platforms in theater. Utilizing a steady stream of geospatial information from various support organizations, the battlespace picture is constantly refined. Terrain, weather, asset location, enemy location, imagery, and any number of other overlays can be combined into one multi-dimensional view of the battlespace. A combination of these overlay parameters is then sensed and utilized for navigation (sensing the fused information rather than components of it). Navigation systems

aboard individual units will evolve from platform-centric to network-centric sensors, removing the dependency of navigation on a single instrument. Rather than sensing simply position related to time, the battlespace itself is sensed. An idea at the very core of NCW's Cooperative Engagement Capability[14].

CAN WE GET THERE FROM HERE?

The weak link in this NCW-based navigation theory is the connecting infrastructure or linking capability. Current C2 architectures such as the Global Command and Control System (GCCS) and tactical data systems such as the Navy Tactical Data System (NTDS) are inadequate by most standards. Managing the volume of information that an NCW-based military will require indicates a need for new C2 systems and their associated infostructure. As with most technology today, obsolescence comes at a rapid pace.

Considering our current technology, initiatives, and research we have the means to build C2 systems capable of vastly improved efficiency and utility. Commercial-off-the-shelf software packages perform similar fusion functions in commercial and educational geospatial information systems (GIS) today. The National Imagery and Mapping Agency (NIMA), the Naval Oceanographic Office (NAVO), and the individual services have already begun using commercial GIS software packages to fuse geospatial data into three-dimensional products. NATO forces now have common standards for digital data and most countries now use the World Geodetic Standard 84 (WGS 84) as a common geospatial reference. Recent space shuttle missions, using radar to map the surface of the Earth, will introduce complete, high-resolution topography for use in future geospatial information systems. NAVO has already begun a move towards true, real-time, fused data as a result of its Rapid Environmental Assessment initiative[15].

Hardware technology is advancing as well. Airborne lasers can now scan the littoral regions for bathymetry and near-shore topography. We have 40 years of gravity measurement experience and now have instruments capable of gravity navigation. Remotely-controlled underwater vehicles, operated from submarines, can perform mine scans and bathymetry under the sea while radio-controlled aircraft collect imagery and environmental intelligence above the surface. In the near future soldiers and vehicles equipped with digital sensors may be able to relay streams of data to the C2 network. Add to this our steadily improving satellite, radar and electronic warfare capabilities and we are able to sense almost any feature of the battlespace. All of this data can be made available to the navigation data subset. There are some technological hurdles including sensor refinement and automatic feature recognition for imagery analysis, but steady progress is being made in these areas.

Our military GIS infrastructure is a huge, relatively untapped resource that, when developed, will provide the joint commander unheard of abilities to see and exploit the battlespace. Getting this information into the navigation infostructure is a matter of removing narrow, discrete channels of information flow and providing it in a common, usable form. All of our current geospatial information including terrain imagery is supplied in a pull process from the NIMA, NAVO or various intelligence organizations. In other words the end user requests specific products to fill a need. This involves time and results in single-purpose products such as charts, maps, imagery and environmental analysis. NIMA and NAVO are well on their way to supporting a push-pull methodology where key information is automatically fed into the C2 information flow. When a Joint Commander enters an area of operation, the back-plane or background information for the theater should already be in place. Netted sensors and individual navigation systems will supply additional real-time

information to the Commander. All of this descriptive information, sensed through a variety of sensor types, will provide multi-dimensional navigation capability. GPS, magnetic, gravity, terrain recognition, inertial, digital celestial and other unrealized parameters will feed a very precise, robust navigation architecture unperturbed by loss of any single or even multiple-sensor navigation method[16]. Command and control functions for the Joint Commander will never be jeopardized by loss of navigation information.

Large, stable platforms such as aircraft carriers, large-deck amphibious ships or even shore sites are likely to possess larger suites of navigation sensors. A typical aircraft carrier might possess GPS as the primary sensor, gravity gradiometers, fathometers and inertial systems as the backups, and a host of other multi-purpose sensors as additional background information feeds. GPS, when available, will provide error control over the other sensors. In the event of a GPS failure, gravity (which has no drift errors) will become the primary sensor. Additionally, in this networked structure, other units with operational GPS receivers can link their battlespace picture to the carrier and provide further error control. The result will be a complete, unbroken picture of the battlespace, linked in real time to all participants and the C2 architecture. Ultimate control over the picture will remain with the Joint Commander or delegated subordinate through a series of filtering capabilities.

CONCLUSIONS AND RECOMMENDATIONS

> ***"Those who do not know the conditions of mountains and forests, hazardous defiles, marshes and swamps, cannot conduct the march of an army. Those who do not use local guides are unable to obtain the advantages of the ground."***
>
> Sun Tzu[17]

Our military is moving rapidly toward a Network-Centric force. To discount this contradicts every new development in C2 and hardware we see today. The Joint Staff has

identified Battlespace Awareness, Information Transport and Processing, and Information Operations as the three Information Superiority Challenges in implementing NCW[18]. Knowing the position and movement of all units, friend or foe, is the major component of battlespace awareness for the Joint Commander. If we fail to develop our capacity to control this information, we are exposing our forces to a critical vulnerability in the battlespace of the future. Getting this same information to all of our forces in real time is the challenge of transport and processing. All 3 critical factors listed above reflect our need for a more robust, synergistic and network-centric method of obtaining and distributing navigation data. Failure of any operator to receive navigation data affects mission accomplishment and the network as a whole. Current, platform-centric navigation is not sufficient to support the military in the age of NCW and reveals a critical weakness in our command and control system. Navigation must be part of the three-dimensional battlespace grid: always available and in a form that can be readily exported to forces denied organic navigation capability. GPS cannot be relied upon as the sole precision navigation source, nor can any other single method. Navigation, like any other important parameter, must be a combination of all available information providing fused data and total reliability. Combat success will depend on the ability of the Joint Commander to master the flow and control of navigation information to his forces.

More and more, Joint Commanders are being called upon to execute highly complex operational plans with precise, discriminate weapons systems. Our newest generation of weapons, while lethal and efficient, have the most exacting requirements for their guidance to target. Our forces are becoming smaller, faster, and perhaps more vulnerable to the effects of friction as we advance towards a network-centric military. One commodity Joint

Commanders of the future cannot do without is the complete knowledge *and* control of geospatial information in the battlespace.

NOTES

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[1] VADM Arthur K. Cebrowski and John J. Garstka. "Network-Centric Warfare: Its Origin and Future." Proceedings on line. <http://www.usni.org/Proceedings/ Articles98/ PROcebrowski. htm> (20 Dec 1999)

[2] Other GPS-reliant weapons systems are listed in Appendix A.

[3] David S. Alberts, John J. Garstka, and Frederick P. Stein. Network Centric Warfare: Developing and Leveraging Information Superiority (Washington, D.C.: CCRP Publication Series, 1999), 51-208.

[4] Rex Buddenberg. <budden@nps.navy.mil> "GPS Jamming." 10 Jan 00, 12 Jan 00, 18 Jan 00. Personal e-mail. (18 Jan 00). Mr. Buddenberg is an instructor in radio-navigation at the Naval Postgraduate School in Monterey, CA.

[5] I. Borza and I. Fejes. "GPS Interference in Hungary". 5th International Seminar on GPS in Central Europe. (Penc, Hungary: 1999) <http://www.sgo.fomi.hu/gps/publ/gps-rfi.htm> (02 Jan 2000)

[6] Vulnerabilities of GPS are discussed in Appendix A.

[7] Extended Range Guided Munitions are rocket-assisted, GPS/inertial-guided projectiles fired from a modified naval 5-inch gun. More information is available at: <http://surfacewarfare.navy.mil/n86/ergm.html>. Tactical Tomahawk is a new, lower-cost land-attack missile which can be configured to use GPS as its guidance mechanism in lieu of the current terrain contour mapping and digital scene mapping. More in formation can be found at: <http://surfacewarfare.navy.mil/n86/latomhwk.html>

[8] Current C2 systems include the Global Command and Control System - Maritime (GCCS-M) which was formerly known as the Joint Maritime Command Information System (JMCIS). The system provides global, theater and area plotting of forces with information overlay capability. Much of the data is time late in the present configuration.

The Navy Tactical Data System (NTDS) is a tactical C2 system utilizing real-time to near real-time data linking between platforms in an area of operation. Encrypted data links such as Link 11 are utilized for data transfer.

[9] Carl von Clausewitz, On War, Michael Howard and Peter Paret, ed. (Princeton: Princeton University Press, 1976), 110.

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[12] Alberts, 90.

[13] Ibid, 129-145.

[14] Ibid, 141.

[15] RADM W. G. "Jerry" Ellis, Network Centric Oceanography in USW, National Defense Industrial Association Undersea Warfare Spring Conference (np: 2 March 1999) <http://oceanographer.navy.mil/ndia.html> (25 Nov 1999)

[16] A description of selected navigation technologies is discussed in Appendix C.

[17] Sun Tzu, The Art of War, Samuel B. Griffith, translator (New York: Oxford University Press, 1963), 104.

[18] LtGEN John L. Woodward, "Statement," U.S. Congress, House, Armed Services Committee, Information Superiority, Hearings before the Armed Services Committee, 106th Congress, 23 Feb 1999. <http://www.house.gov/hasc/testimony/106thcongress/99-02-23woodward.htm>

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APPENDIX A: U.S. WEAPONS SYSTEMS HEAVILY DEPENDENT UPON GPS

System	GPS used for:	Backup without GPS correction:
AGM-84 Harpoon (SLAM and SLAM-ER) Standard Land Attack Missile	Primary guidance updates to inertial system	Inertial
AGM-86C/D (CALCM) Conventional Air-Launched Cruise Missile	Primary guidance updates to inertial system	Inertial
AGM-154A (JSOW) Joint Standoff Weapon	Primary guidance updates to inertial system	Inertial
AGM-158 (JASSM) Joint Air to Surface Standard Missile	Primary guidance updates to inertial system	Inertial
(ATACMS M39) (ATACMS/BAT) Army Tactical Missile System BAT: "Brilliant" Anti-armor version	Primary guidance updates to inertial system	Inertial
BGM-109 (TACTOM) Tactical Tomahawk	Uses GPS/INS guidance package instead of GPS/TERCOM/DSMAC of other Tomahawks	Inertial
GBU-15 (ITAG mod)	Initiates primary guidance system prior to release	Cannot release without initialization
GBU-24	Primary guidance	Inertial
GBU-29, 30, 31, 32 (JDAM) Joint Direct Attack Munition	Primary guidance	Inertial
GBU-36, 37 (GAM) GPS Aided Munition	Primary guidance	Inertial
(Guided MLRS) M30 Guided Multiple Launch Rocket System	Primary guidance	Ballistic

APPENDIX B: VULNERABILITIES OF GPS IN MILITARY USE

Many potential problem areas exist for GPS in the military environment. Perhaps the most serious is the risk of jamming from relatively unsophisticated, man-portable equipment. Russia now markets a jammer for several thousand dollars and no doubt there are other countries pursuing the same asymmetrical warfare path. There are programs today in the DoD to reduce the vulnerability of GPS to jamming, but the threat cannot be removed altogether and threat reduction is expensive. The next generation of GPS satellites will have enhanced jam resistance and greater output power, but this is not a quick fix and will only *reduce* the threat. GPS is and will continue to be a radio-frequency-based system. Where there is RF energy, it can be jammed. At only 25 watts of satellite output power, the signal level on the ground is very weak and is well below the background RF energy level in the environment.

Spoofing or tricking GPS is a more difficult task for even a technologically advanced country. While it happens inadvertently, there is no evidence to date that spoofing has occurred directly from hostile efforts. Differential GPS, though limited to relative small areas at a time, renders spoofing virtually impossible. As our bandwidth problems proliferate, inadvertent spoofing and jamming is likely to occur more frequently. Additionally, new electromagnetic-pulse (EMP) weapons present a new generation of asymmetrical threat since all but the most heavily shielded electronics will be vulnerable.

Satellites are susceptible to meteors, sunspot activity and failure. If 2 or more satellites fail at once, GPS availability begins to decline. With any space-based system, natural occurrences will pose some level of risk no matter what precautions are taken.

Over-availability is a relatively new problem area for DoD GPS usage. With modern commercial receivers, even Selective Availability does not pose a significant reduction in precision for other countries exploiting our own military navigation system. Strong pressure from civilian interests has posed the risk of not being able to cut off civilian SPS during wartime. Additionally, DoD has purchased huge numbers of commercial receivers for use by troops in the field. At least 7,000 commercial units were used by troops during Desert Shield/Storm. Sharing the wealth may be a big problem for GPS in the future as more and more commercial and foreign-military systems incorporate GPS.

APPENDIX C: NEW NAVIGATION TECHNOLOGY

Gravity

Surveying teams from the Naval Oceanographic Office (NAVO) have been measuring gravity for many years in support of the strategic weapons programs. Gravity information is now used in both military and commercial applications. Gravity navigation systems measure the local gravity field and can produce a 3-D picture allowing the operator to "view" the surrounding terrain or bathymetry. By correlating gravity features with high-resolution charts or maps, accurate navigation information can be obtained. Gravity systems cannot be jammed or spoofed and offer excellent reliability and durability. Gravity systems do not provide the precision of military GPS but do achieve 200-400 foot accuracy. This performance is repeatable in any electronic or environmental situation making gravity a good choice as an integral part of a GPS-based system. Current configurations are not suited to ground vehicles or high performance aircraft due to vibration interference. Actual tests aboard small commercial aircraft, U.S. submarines, and large naval vessels and aircraft have produced excellent results. This method appears very well suited to submarines, surface ships and larger aircraft.

Digital Celestial

Celestial navigation with a twist may offer another method in the future. Using a system similar to that on some strategic weapons, a digital snap-shot of the stars (perhaps even in daylight) would be taken and instantly computer analyzed. Utilizing a database of star maps, the system would locate itself and provide input into the integrated navigation architecture. Limitations are significant for surface based systems: cloudy skies, fog, natural and man-made obscurations and spoofing by light sources (i.e. laser dazzling). On the other hand, high-flying aircraft would be able to achieve good results and the method would seem to be ideally suited to reconnaissance aircraft, strategic bombers and extra-atmospheric weapons.

Digital Scene Matching

In use for years as Digital Scene Matching Area Correlation (DSMAC) in the Tomahawk program, digital scene matching has great potential. With improvements in computing power and digital imagery, whole new avenues in scene matching are possible. These systems "look" at their surroundings through optical, digital or other sensor methods and match the picture obtained to a known database. Natural features, cities and perhaps even other more exotic parameters may be included in the database. Many features would be very difficult to spoof and, as evidenced by the Tomahawk's success, the method has real utility in military applications.